

# Triggered Star Formation in a Massive Galaxy at $z=3.8$ : 4C 41.17<sup>1</sup>

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## ABSTRACT

We present deep spectropolarimetric observations obtained with the W. M. Keck Telescope of the very high redshift ( $z=3.79786\pm0.0024$ ) radio galaxy 4C 41.17. We find that the bright, spatially extended rest-frame UV continuum emission from this galaxy, which is aligned with the radio axis, is unpolarized ( $P_{2\sigma} < 2.4\%$ ). This implies that scattered AGN light, which is generally the dominant contributor to the rest-frame UV emission in  $z \sim 1$  radio galaxies, is unlikely to be a major component of the UV flux from 4C 41.17. The resulting total light spectrum shows absorption lines and P-Cygni-like features that are similar to those detected in the spectra of the recently discovered population of star forming galaxies at slightly lower ( $z \sim 2 - 3$ ) redshifts. It may be possible for a galaxian outflow to contribute partially to the absorption line profiles of the low ionization species; however, it is unlikely that the high velocity wings of the high ionization lines are dominated by a galaxian wind since the outflow mass implied by the absorption line strengths is very large. The detection of the S V $\lambda$ 1502 stellar photospheric absorption line, the shape of the blue wing of the Si IV profile, the unpolarized continuum emission, the inability of any AGN-related processes to account for the UV continuum flux, and the overall similarity of the UV continuum spectra of 4C 41.17 and the nearby star-forming region NGC 1741B1 strongly suggest that the UV light from 4C 41.17 is dominated by young, hot stars. If all of the UV emission is due to starlight from a young population, the implied star-formation rate is roughly  $140 - 1100 h_{50}^{-2} M_{\odot}/\text{yr}$ . The deep spectroscopy presented here combined with the morphology of the system at radio and optical wavelengths and the possibly comparable ages for the radio source structure and the UV stellar population suggest that star formation in 4C 41.17 was triggered by the expansion of the radio source into the ambient medium. Our current observations are consistent with the hypothesis that 4C 41.17 is undergoing its major epoch of star formation at  $z \sim 4$ , and that by  $z \sim 1$  it will have evolved to have spectral and morphological properties similar to those observed in known  $z \sim 1$  powerful radio galaxies.

*Subject headings:* galaxies: active — galaxies: individual (4C 41.17) – galaxies: formation – galaxies: evolution – galaxies: stellar content

## 1. Introduction

Until recently, radio source samples provided astronomers with the only known galaxy-like objects at cosmological distances. Currently, three of the four brightest known visible galaxies at redshifts  $z \gtrsim 4$  are radio galaxies. One of the most intriguing properties of powerful radio galaxies at high-redshift is that their spatially extended UV morphology is preferentially aligned with the major axis of their radio emission (McCarthy et al. 1987, Chambers et al. 1987). Several possible explanations have been proposed for this ‘alignment effect’ (see McCarthy 1993 for a recent review); the two most compelling of these are (1) that the UV morphology is dominated by dust- and electron-scattered light from an anisotropically radiating nuclear source (e.g., Tadhunter et al. 1988), and (2) that the UV morphology is the result of star-formation triggered by the radio source as it expands into the dense ambient medium (e.g., De Young 1981, 1989; Rees 1989; Begelman & Cioffi 1989). Although there is circumstantial evidence at low redshift for radio sources triggering star-formation (e.g., in Minkowski’s Object, van Breugel et al. 1985; in 3C 285, van Breugel & Dey 1993; and in the Abell 1795 cD galaxy, McNamara et al. 1996), the majority of powerful  $z \sim 1$  radio galaxies investigated exhibit strong polarization ( $\sim 10\%$ ) of the continuum emission and broad emission lines, a result which confirms that much of the spatially extended rest-frame UV continuum emission in these systems is scattered light from a hidden AGN (di Serego Alighieri et al. 1989, Tadhunter et al. 1988, Jannuzi & Elston 1991, Jannuzi et al. 1995, Dey et al. 1996, Cimatti et al. 1996, 1997). The fractional polarization in most of the  $z \sim 1 - 2$  powerful radio galaxies investigated thus far show either no significant variation of polarization with wavelength (i.e.,  $P(\lambda) \approx \text{constant}$ ) or, in a few cases, polarization increasing towards shorter wavelengths. In addition,  $z \sim 1$  radio galaxies of lower radio power (i.e., in which the AGN makes an insignificant contribution to the UV light) show underlying stellar populations that are both dynamically and spectrally old (e.g., Spinrad et al. 1997, Dunlop et al. 1996, Rigler et al. 1992), providing further evidence that triggered star-formation is not the dominant process responsible for the alignment effect in  $z \sim 1$  radio galaxies.

Despite the success of the scattering hypothesis in explaining the alignment effect in most  $z \sim 1$  radio galaxies, the processes responsible for its origin in the highest redshift systems remain open to debate. The  $z \gtrsim 3$  radio galaxies are faint, and until now have remained beyond the reach of most modern polarimeters.

In this paper, we present spectropolarimetric observations of the  $z = 3.80$  radio galaxy 4C 41.17. The broad-band spectral energy distribution of 4C 41.17 was first investigated by Chambers et al. (1990), who suggested that starlight from a young population produced the bulk of the observed optical and near-IR continuum emission, and that the alignment of the UV morphology with the radio source axis is most likely due to star-formation triggered by the radio source. Although there is close spatial coincidence between the compact UV and radio continuum emitting components (Miley et al. 1992), the observed UV emission is vastly in excess of that which can be produced by synchrotron emission from relativistic electrons responsible for the radio emission, or inverse Compton scattering of the radio or cosmic microwave background photons off these electrons (Carilli et al. 1994). Our data demonstrate that the UV light in this system is not dominated by scattered light from an active nucleus, but instead is very likely to be dominated by starlight from a young stellar population. We discuss our observations of this high-redshift galaxy in the context

of a scenario where the  $z \sim 4$  powerful radio galaxies are the progenitors of the  $z \sim 1$  population.

Throughout this paper we assume that  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0.1$ . The scale at  $z = 3.80$  is then  $10.8 h_{50}^{-1} \text{ kpc}''$  and the lookback time is nearly  $14.3 h_{50}^{-1} \text{ Gyr}$ , or 86% of the age of the universe. In comparison, for  $q_0 = 0.5$  the angular scale is  $6.6 h_{50}^{-1} \text{ kpc}''$  and the lookback time is  $11.8 h_{50}^{-1} \text{ Gyr}$ , or 90% of the age of the universe.

## 2. Observations

We observed 4C 41.17 on the nights of U.T. 1996 December 9 and 10 using the spectropolarimetric mode of the Low Resolution Imaging Spectrometer (Oke et al. 1995, Goodrich et al. 1995) at the Cassegrain focus of the Keck II Telescope. The observations were obtained using the 400 line/mm grating ( $\lambda_{\text{blaze}} = 8500 \text{ \AA}$ ; dispersion =  $1.86 \text{ \AA/pixel}$ ) to sample the wavelength range  $\lambda\lambda 5500\text{--}9280 \text{ \AA}$  (corresponding to  $\lambda\lambda 1146\text{--}1933 \text{ \AA}$  in the rest frame of 4C 41.17), and a  $1''$  wide slit (effective resolution FWHM in the observed frame of  $\approx 8 \text{ \AA}$ ). The LRIS detector is a Tek 2048<sup>2</sup> CCD with  $24 \mu\text{m}$  pixels with a pixel scale of  $0''.214 \text{ pix}^{-1}$ . The CCD read noise during our run was  $6.2 e^-$  and the gain was  $\approx 2.1 e^-/\text{ADU}$ .

Over the two nights, we obtained a total of seven sets of observations (three on Dec. 9 and four on Dec. 10) with the spectrograph slit oriented along the major axis of the rest-frame UV continuum emission from the galaxy ( $\text{PA} = 76.5^\circ$ ). Each set is comprised of observations made in four waveplate positions ( $0^\circ, 45^\circ, 22.5^\circ, 67.5^\circ$ ) which sample the electric vector in four position angles on the sky ( $76.5^\circ, 166.5^\circ, 121.5^\circ, 31.5^\circ$  respectively). The exposure time per waveplate position was 20 minutes for each set, resulting in a total exposure time of 140 minutes per waveplate position, and 9.33 hours for the total spectrum. After two sets of observations, we reacquired the galaxy using an offset from a nearby star. Our first night was affected by minor telescope focus problems and poor seeing, but the seeing during our second night was good ( $\sim 0.8 - 1''$ ) and conditions were photometric. During our observations the parallactic angle rotated during our observations from  $\text{PA}_{\text{parallactic}} \approx 75^\circ$  to  $-75^\circ$  (hour angle  $-3^h$  to  $+3^h$ ), and the maximum airmass was 1.45.

In order to calibrate the instrumental polarization position angle ( $\text{PA}_{\text{pol}}$ ) correction and the polarization efficiency, we observed the star BD+28°4211 through UV and IR polaroid filters in four waveplate positions. We find the  $\text{PA}_{\text{pol}}$  correction to be very stable (consistent with that measured on previous runs with the polarimeter) and the polarization measurement efficiency to be  $\approx 1.000 \pm 0.007$ ; hence, no correction for the latter was made to the data. We also observed the zero polarization standard GD 319 as a check on any residual polarization effects: our measurement yields  $P < 0.16\%$  ( $2\sigma$ ). The electric vector position angle zero point offset was calibrated using observations of the polarization standard stars HD204827 and HD245310 (Schmidt, Elston, & Lupie 1992); our measurements are in very good agreement with the published values.

The data were corrected for overscan bias and flat-fielded using internal lamps taken immediately preceding and following the observations. The flux calibration was performed using observations of Feige 110 and Feige 34 (Massey et al. 1988, Massey & Gronwall 1990) obtained both with and without an order sorting OG570 filter in order to correct for the second order light contamination in the spectral region  $\lambda > 7500 \text{ \AA}$ . All of the spectroscopic reductions were performed

using the NOAO IRAF package. The spectropolarimetric analysis was carried out using our own software, and is based on the methods described in Miller, Robinson, & Goodrich (1988).

### 3. Results

#### 3.1. Polarimetry

Our polarimetric results are presented in Table 1. Since 4C 41.17 is very faint (peak continuum  $V$  surface brightness  $\approx 21.2$  mag/□′′), the continuum polarization was determined in large spectral bins (cf., Dey et al. 1996). For each wavelength bin, we tabulate the normalized linear Stokes parameters,  $Q = (I_0 - I_{90})/(I_0 + I_{90})$  and  $U = (I_{45} - I_{135})/(I_{45} + I_{135})$ , where  $I_\theta$  is the effective intensity of light polarized with its electric vector at position angle  $\theta$ . Since the polarization is low, we also tabulate an unbiased estimate of the percentage polarization  $P_{unb} \equiv \pm\sqrt{|P^2 - \sigma_P^2|}$ , where  $P_{unb}$  is defined to be negative if  $P < \sigma_P$  (Wardle & Kronberg 1974, Simmons & Stewart 1985). The continuum emission, sampled in these bins over the  $3''42 \times 1''0$  extracted aperture (i.e., sampling the brightest continuum emitting region in the galaxy), is found to be unpolarized, with formal  $2\sigma$  upper limits of  $P_{unb} < 2.4\%$  in the wavelength range  $\lambda\lambda 1223 - 1535$  (i.e., between Ly $\alpha$  and C IV), and  $< 7\%$  in the region  $\lambda\lambda 1645 - 1895$  (i.e., between He II and C III]). Within our measurement errors, the narrow emission lines appear to be unpolarized. The Galactic latitude of 4C 41.17 is  $17.5^\circ$  and the interstellar percentage polarization is estimated to be low ( $E(B-V) \approx 0.15$ , which implies  $P_{ISM} < 1.4\%$ ; Burstein & Heiles 1982; Appenzeller 1968, Mathewson & Ford 1970). A slightly better constraint on the interstellar polarization results from the formal  $2\sigma$  upper limit of  $< 0.9\%$  for the polarization of the narrow component of the Ly $\alpha$  emission line.

The fractional polarization of the continuum emission in 4C 41.17 is therefore much lower than that measured in the lower redshift ( $z \sim 1 - 2$ ) radio galaxies, which are generally found to have rest-frame UV continuum percentage polarizations of  $\gtrsim 10\%$  (di Serego Alighieri et al. 1989, Cimatti et al. 1996, 1997, Dey et al. 1996). This difference in polarization is not simply the result of the different rest-frame wavelength ranges sampled at  $z \approx 3.8$  and  $z \sim 1 - 2$ . Spectropolarimetric observations of the  $z \sim 1$  radio galaxies show either no significant wavelength dependence of the continuum polarization in the near UV (after accounting for dilution by starlight) or, in a few cases, some evidence for increasing  $P$  with decreasing wavelength. Moreover, the spectropolarimetry of 4C 41.17 may be directly compared with existing observations of 3C 256, a  $z \approx 1.82$  powerful radio galaxy for which spectropolarimetric observations have been made down to  $1400\text{\AA}$  in the rest frame (Dey et al. 1996). The continuum polarization of 3C 256 at wavelengths shortward of C IV is high ( $\approx 10\%$ ) and  $P(\lambda)$  is roughly wavelength independent between  $1400\text{\AA}$  and  $2700\text{\AA}$ . These results suggest that, in comparison, 4C 41.17 has intrinsically low polarization.

#### 3.2. Emission Line Spectrum

The summed spectrum of 4C 41.17 was corrected for Galactic absorption using the extinction curve of Cardelli et al. (1989) and an  $E(B - V) = 0.15$ . The parameters of the emission and

absorption lines listed in Tables 2 and 3 were derived from the dereddened spectrum (using SPEC-FIT in IRAF; Kriss 1994) extracted in a  $2''.1 \times 1''.0$  aperture centered on the brightest region of the galaxy (Figure 1). The redshift of the galaxy determined from the He II  $\lambda 1640$  emission line is  $3.79786 \pm 0.00024$ ; as expected, the resonance lines (Ly $\alpha$ , N V, Si IV and C IV) result in a slightly higher redshift, since the blue side of the lines are modified by associated absorption. The C III]  $\lambda 1909$  emission line may be slightly blue shifted (by  $\approx 175 \pm 110 \text{ km s}^{-1}$ ) relative to the systemic velocity determined from He II emission line, but since it is also much broader (see below) than any of the other emission lines, we consider it likely that it arises in a different region than the bulk of the narrow-line emitting gas. The He II redshift is consistent with (but possibly slightly redshifted by  $\sim 135 \text{ km s}^{-1}$  relative to) the average redshift determined from the low ionization absorption lines. Since most of the absorption lines may be contaminated by (stronger) emission and have asymmetric profiles, in this paper we adopt the He II redshift as the systemic redshift of the galaxy.

The ratios of the narrow emission line strengths of C III], C IV and He II can be well matched by a simple photoionization model incorporating a power-law ionizing source with  $\alpha = -1.5$  ( $f_\nu \sim \nu^\alpha$ ), a high ionization parameter  $U \lesssim 0.1$  and solar metallicity clouds (e.g., Villar-Martin, Tadhunter & Clark 1997). The large C IV/C III] ratio also favors a geometry where the illuminated sides of the line-emitting clouds are viewed directly (Villar-Martin et al. 1996); if the photoionizing source is the central AGN, this implies that the bulk of the line-emitting region (the NE part of the galaxy) lies on the *far* side of the AGN nucleus. This geometry is also supported by the radio rotation measure (Carilli et al. 1994), which implies a larger Faraday optical depth to the eastern part of the source than to the western lobe.

The profiles of both Ly $\alpha$  and C III]  $\lambda 1909$  reveal relatively broad components. On fitting these lines with a two-Gaussian model, we find that the broad components have FWHMs of  $\approx 1100 - 1400 \text{ km s}^{-1}$  (e.g., Figure 2). Although large, these widths may be simply a high-velocity component of the emission line gas resulting from the interaction of the radio source with the ambient medium, or due to entrainment of the gas in the radio jet. The fact that the emission lines are unpolarized supports this suggestion. Alternatively, the broad components may arise in the nuclear broad-line region, and may imply that there is a small contribution to the UV continuum and line flux from the active nucleus. Although the measured FWHM of the emission lines are smaller than those typically measured in the broad line regions of steep spectrum radio-loud quasars ( $\text{FWHM}_{\text{QSO}} \sim 4000 \text{ km s}^{-1}$ , with almost all having  $\text{FWHM}_{\text{QSO}} \gtrsim 2000 \text{ km s}^{-1}$ ; e.g., Brotherton et al. 1994, Corbin 1991), the rest-frame equivalent width of the broad component of the C III] emission line ( $\approx 13 \text{ \AA}$ ) is roughly comparable to that observed in these quasars. It is therefore possible that there may be some contribution from AGN light to the UV flux, at least at wavelengths  $\lambda_{\text{rest}} \sim 1900 \text{ \AA}$ . We note that although we do not detect any significant polarization of the C III] line, the errors are large in this part of the spectrum; the  $2\sigma$  upper limit from these data is large ( $< 11\%$ ), and therefore does not provide a useful constraint.

### 3.3. Absorption Line Spectrum

One of the most remarkable results from our observations of 4C 41.17 is the detection of strong absorption features in its total light UV spectrum. Figure 3 shows the total light spectrum of the brightest  $2''.1 \times 1''.0$  region of the galaxy (smoothed using a 5-pixel boxcar), which clearly shows strong absorption lines of Si IV, Si II, C IV, C II, O I and Ly $\alpha$ . Some of these features have ‘P-Cygni-like’ profiles, i.e., an emission component juxtaposed with a blue-shifted absorption component. P-Cygni-like profiles may arise either in stellar winds or be the result of a different mechanism (e.g., galaxian outflows); we discuss the possible physical origin of these profiles in 4C 41.17 in § 4.2. The spectrum of 4C 41.17 in this regard is similar to that of actively star-forming regions in nearby galaxies such as 30 Doradus (Vacca et al. 1995), NGC 4214 (Leitherer et al. 1996) and the B1 star-forming knot in the nearby starburst galaxy NGC 1741 (hereafter referred to as NGC 1741B1, Conti, Vacca & Leitherer 1996; see also Figure 3), and to the  $z \sim 2-3$  population of star-forming galaxies recently discovered by virtue of their Lyman limit absorption (e.g., Steidel et al. 1996, Giavalisco et al. 1996, Lowenthal et al. 1997).

The parameters of the strongest detected absorption lines are listed in Table 3 along with limits on the strengths of known stellar absorption features. The absorption lines that are largely uncontaminated by strong emission have rest-frame equivalent widths of  $\approx 1-2 \text{ \AA}$  (Table 3), and are therefore slightly smaller than in most starbursts systems (e.g., NGC 1741B1 has equivalent widths of  $\approx 2 \text{ \AA}$  for these lines; Conti et al. 1996). Many of the absorption features have asymmetric profiles with blue wings extending to more than  $2500 \text{ km s}^{-1}$  from the line centroid, and some show P-Cygni-like profiles. If we define the systemic velocity to be that measured from the He II emission line, then the absorption troughs associated with Ly $\alpha$  and C IV are blue shifted relative to the systemic velocity by  $\approx 1700 \text{ km s}^{-1}$ , whereas the absorption in the low-ionization species of Si II, C II and O I are at the systemic velocity, or perhaps slightly blue shifted by  $\approx 135 \pm 43 \text{ km s}^{-1}$ . The blue shifts observed in Ly $\alpha$  and C IV are somewhat difficult to determine accurately since these absorption features are contaminated by very strong line emission.

In addition to the absorption lines that are clearly associated with P-Cygni-like emission, there are a few features for which we have only tentative identifications. These features are likely to be either very high-velocity blue-shifted absorption arising in a outflowing gas, or due to foreground (intervening) metal-line systems. The strong absorption feature at  $6555 \text{ \AA}$  appears to be (at the present resolution) a composite of three absorption lines at  $6544.3 \text{ \AA}$ ,  $6560.0 \text{ \AA}$  and  $6573.6 \text{ \AA}$  (Figure 5). The ratios of the first two features suggest that these may be Mg II  $\lambda\lambda 2796.35, 2803.53$  in an intervening system at  $z = 1.340$ . We tentatively identify the  $6573.5 \text{ \AA}$  line with the O V  $\lambda 1371$  wind feature in 4C 41.17. This line is strong in the spectra of O3 giant and supergiant stars (Walborn et al. 1995a). An unambiguous understanding of the true origin of this complex must await higher resolution and higher signal-to-noise ratio data.

Table 3 also lists absorption lines at observed wavelengths of  $6351.5 \text{ \AA}$ ,  $6661.8 \text{ \AA}$ , and  $7256.5 \text{ \AA}$ . These features may correspond to the C II  $\lambda 1335$ , Si IV  $\lambda 1400$ , and Si II  $\lambda 1527$  features blue-shifted by  $\approx 2500 \text{ km s}^{-1}$  from the systemic velocity. Alternatively, the  $6661.8 \text{ \AA}$  feature is more likely to simply be the blue wing of the Si IV absorption profile, and the  $6351.5 \text{ \AA}$  line may correspond to a similar feature at  $\lambda \approx 1322 \text{ \AA}$  observed in NGC 1741B1 (Figure 3). In summary, absorption line

systems physically associated with 4C 41.17 are observed at approximately the systemic velocity defined by the line-emitting gas, with the high-ionization P-Cygni-like lines extending to velocities of  $\gtrsim 1700 \text{ km s}^{-1}$ , and possibly also at  $\approx 2500 \text{ km s}^{-1}$  blue shifted relative to the line-emitting gas.

## 4. Discussion

### 4.1. Scattered Light and Starlight in 4C 41.17

The majority of radio galaxies at redshifts  $z \sim 1$  exhibit UV continuum polarization, with the position angle of the electric vector generally perpendicular to the major axis of the UV extent (e.g., Tadhunter et al. 1988, di Serego Alighieri et al. 1989, Jannuzi & Elston 1991, Jannuzi et al. 1995, Dey et al. 1996, Cimatti et al. 1996, 1997). In almost all known cases, the percentage polarization is large ( $\gtrsim 10\%$ ) at rest-frame UV wavelengths and, in a few cases, monotonically decreases with increasing wavelength. In a few well-studied cases, broad emission lines have been detected both in the total light and polarized flux spectra. These results have led to the conclusion that the spatially extended, aligned UV morphologies of the  $z \sim 1$  powerful radio galaxies are largely a result of scattered light from the AGN. 4C 41.17 is therefore an exception to the rule — the low measured percentage polarization does not support the hypothesis that the UV emission is dominated by light from the AGN.

However, the lack of polarization does not necessarily *prove* that the UV continuum emission from 4C 41.17 does not have a scattered AGN contribution. The polarization could be diluted by geometrical effects resulting from averaging over large areas (our spectral extraction covers an aperture of  $3''.2 \times 1''.0$ ) which have different polarization angles. In order to investigate this possibility, we measured the polarization in the UV continuum between Ly $\alpha$  and CIV as a function of spatial position along the slit from our best seeing data. Within the errors, there is no convincing detection of polarization in the extended continuum. It is also possible to dilute the fractional polarization by multiple scattering. This would require that the scattering be due to dust particles rather than electrons, which would in turn result in large reddening and extinction of the spectrum; no significant extinction or reddening is observed. The upper limit on the estimated extinction ( $E(B-V) \lesssim 0.1$ ) corresponds to a dust optical depth at a rest wavelength of  $1500 \text{ \AA}$  of  $\tau_{1500 \text{ \AA}} \lesssim 0.9$ , which should not result in significant dilution of  $P$  by multiple scattering. Finally, some theoretical models suggest that the dust scattering efficiency may drop sharply at wavelengths less than  $\lambda \sim 2200 - 2600 \text{ \AA}$  (A. Laor, personal communication). Although such a feature has never been observed in the scattered light UV spectra of Galactic reflection nebulae (e.g., Calzetti et al. 1995), if this were indeed the case, our limits may be consistent with dust scattering contributing significantly to the longer wavelength radiation  $\lambda \gtrsim 2600 \text{ \AA}$ , but very little to the shorter wavelength radiation. We therefore conclude that the UV spectrum, at least at wavelengths  $\lambda_{rest} \sim 1500 \text{ \AA}$ , is largely uncontaminated by scattered AGN light.

Is it possible that other AGN-related processes dominate the UV continuum emission from 4C 41.17? Due to the strong Ly $\alpha$  emission observed in 4C 41.17, it has been suggested by Dickson et al. (1995) that the UV continuum emission in 4C 41.17 may be dominated by thermal continuum emission. The blue ( $F_\lambda \propto \lambda^{-1.8}$ ) UV continuum spectrum of 4C 41.17 indicates that it is unlikely



that the recombination continuum emission from hydrogen dominates the continuum emission in the region between  $\text{Ly}\alpha$  and C IV. The flux in the  $\text{Ly}\alpha$  emission line can provide a fairly good estimate of the contribution of the nebular emission to the UV spectrum in our  $2''.1 \times 1''.0$  aperture. However, this resonance line is easily attenuated by dust, and instead a more reliable estimate may be derived from the He II  $\lambda 1640$  emission line. For a solar metallicity gas ionized by a power-law continuum (ionization parameter  $\log U = -1.8$  to  $-2.8$ ), the typical ratio of  $\text{Ly}\alpha/\text{He II}$  is  $\approx 20$ . Hence, assuming that  $F_{\text{total}}(\text{Ly}\alpha) \approx 1.1 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ , and that the typical temperature of the line-emitting gas is  $10^4 \text{ K}$ , the total contribution of recombination and bremsstrahlung emission from H I at  $\lambda < 2600 \text{ \AA}$  is  $< 1 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ , or  $< 7\%$  of the UV continuum emission (e.g., Osterbrock 1989, Brown & Mathews 1970). Hence, it is unlikely that any obvious AGN-related process (i.e., scattered light, thermal bremsstrahlung and recombination emission) contributes significantly to the UV continuum emission from 4C 41.17, at least at rest wavelengths  $\lambda_{\text{rest}} \sim 1500 \text{ \AA}$ . We are therefore left with the possibility that this UV continuum emission is dominated by starlight.

It is possible, however, that the longer wavelength radiation has a larger contribution from AGN emission. For wavelengths longward of the He II  $\lambda 1640$  line, the strong telluric OH emission precludes a high signal-to-noise measurement of the fractional polarization, and the upper limits from our measurements are less restrictive (e.g.,  $P_{2\sigma} < 7\%$  for  $1645 < \lambda_{\text{rest}} < 1885 \text{ \AA}$ ). In addition, the C III] emission line is observed to have a relatively broad component with a rest-frame equivalent width similar to that observed in quasars, and the redshift determined from the line is slightly different from that determined from the He II narrow line which suggests that this line arises in a different region (at a different velocity) from the bulk of the narrow-line emitting gas. It is therefore possible that there is a significant AGN contribution to the emission at the longest observed wavelengths. Indeed, the observed continuum emission from the central body of the galaxy can be fairly well-modelled by a double power-law: the region between  $\text{Ly}\alpha$  and C IV has a  $F_\lambda \propto \lambda^{-1.8}$  dependence, whereas the spectral region between He II and C III] is roughly wavelength independent. The hypothesis of an AGN contribution rising to redder wavelengths would imply that the AGN is intrinsically much redder ( $\beta > +1.7$ , where  $F_\lambda^{\text{AGN}} \propto \lambda^\beta$ ) than that observed in the luminous, steep-spectrum radio-loud quasars (typically  $\beta \sim -1$ ). In light of the submillimeter detection of warm dust emission from 4C 41.17 (Dunlop et al. 1994), it is possible that its active nucleus is still enshrouded in dust and heavily reddened at least along our line of sight. If the polarization in the region  $1645 < \lambda_{\text{rest}} < 1885 \text{ \AA}$  is real, it is noteworthy that the electric vector position angle is parallel to the radio axis, rather than perpendicular as it is in most  $z \sim 1$  radio galaxies; this result suggests a different scattering geometry or polarization mechanism. Spectroscopic and polarimetric observations at near-IR wavelengths are necessary to determine the AGN contribution, if any, to the observed emission at longer wavelengths.

## 4.2. The Origin of the Absorption Lines

It is of great importance to understand the origin of the absorption lines in a galaxy observed at such an early epoch (for  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $q_0 = 0.1$ ,  $\Lambda = 0$ , the Universe is only 2.2 Gyr old at  $z = 3.8$ ). As discussed in the previous section, the UV continuum emission at  $\lambda_{\text{rest}} \sim 1500 \text{ \AA}$

cannot be adequately explained by AGN-related processes, and is therefore likely to be dominated by starlight. Strong stellar UV continuum emission can be produced by very young populations, in which the integrated UV spectrum is dominated by the flux from hot, high-mass stars. Hence, it is tempting to interpret the UV absorption lines observed in 4C 41.17 as photospheric or dense wind features from hot, young stars. However, it is important to note that most of the strong resonance lines detected near the systemic velocity in the UV spectra of nearby star-forming galaxies are generally dominated by interstellar rather than stellar components (e.g., York et al. 1991). In this section we investigate whether or not the absorption line spectrum of 4C 41.17 contains a component due to starlight, and the possibility that the absorption spectrum can arise in a galaxian outflow.

A clear test of whether or not the UV continuum emission is due to young stars is the detection of stellar photospheric lines which are uncontaminated by interstellar absorption in the integrated spectrum (e.g., C III $\lambda$ 1247, Si III $\lambda$ 1296, Si III $\lambda$ 1417, S V $\lambda$ 1502, N IV $\lambda$ 1720; Leitherer, Robert & Heckman 1995, Heckman & Leitherer 1997, Heckman et al. 1997; M. Pettini personal communication). These lines arise from excited levels (e.g., the lower energy level of the S V $\lambda$ 1502 transition is the 3 $p$ (J=1) level which lies  $\approx 15.8$  eV above ground; Bashkin & Stoner 1975). While these features can be easily formed in the dense, hot winds of early-type stars, they are unlikely to arise in the cooler, less dense interstellar medium. The integrated spectrum of 4C 41.17 shows at least one unambiguous signature of starlight: we detect the weak S V $\lambda$ 1502 photospheric absorption line<sup>3</sup> (Figure 4), with an equivalent width of  $W_\lambda(\text{SV}) \approx 0.4 \text{ \AA}$  in the rest frame. The strength of the S V line in 4C 41.17 is comparable to that observed in nearby starbursts ( $W_\lambda(\text{SV}) \approx 0.5 \text{ \AA}$  in NGC 1741B1). This suggests that AGN light does not contribute significantly to the spectrum at these wavelengths, although the signal-to-noise ratio and resolution of the present data do not provide a strong constraint on this issue. We also marginally detect weak absorption due to stellar photospheric lines of Si III $\lambda$ 1294.6, 1296.7 ( $W_\lambda(\text{SiIII}) \approx 3.7 \text{ \AA}$ ).

The shape of the Si IV absorption profile also indicates that hot stars make a significant contribution to the UV spectrum. Figure 5 shows that the Si IV feature has narrow components that appear slightly blue shifted from the systemic velocity as well as a blue wing that extends to more than  $2500 \text{ km s}^{-1}$  from the systemic velocity. Although the narrow components are almost certainly interstellar, the shape and extent of the blue wing closely resembles that observed in NGC 1741B1 (Figure 5; Conti et al. 1996), where it is believed to arise in hot stellar winds (e.g., Conti et al. 1996, Heckman & Leitherer 1997; in particular, see their Figure 2). Finally, as reported in § 3.3, there is a marginal detection of the O V $\lambda$ 1371 wind feature (Figure 5). If the existence of this feature can be verified with higher resolution data (to separate the O V line from the foreground Mg II absorber), it will provide strong support for the presence of early spectral type O giants and supergiants (Walborn et al. 1995a). We have also searched for other pure photospheric absorption

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<sup>3</sup>The identification of the stellar absorption feature at 1502 Å is uncertain at present; Dean and Bruhweiler (1985) suggest the feature is due to Mn V whereas Willis et al. (1986) identify absorption and nearby emission at 1500-1505 Å in the spectra of WN stars as due to P III and S V. Howarth (1987) attributes the 1501.8 Å feature observed in the UV spectrum of the sdO star HD 128220 to S V. In all cases, the line arises from an excited level and is therefore photospheric. It is observed in the spectra of O stars (Walborn et al. 1995a) and gradually weakens with increasing spectral type; it disappears by mid-B spectral types. Given the relative cosmological abundances of S, P and Mn and their ionization potentials, it is most likely that this feature is S V.

lines (e.g., C III $\lambda$ 1247 and N IV $\lambda$ 1720), but these are undetected in the present data. Unfortunately, the upper limits on the strengths of the undetected lines do not provide any useful constraints or rule out the presence of starlight in the spectrum (see Table 3).

Is it possible for the P-Cygni-like absorption lines to be formed in a galaxian outflow rather than in a stellar wind? Some low-ionization lines such as Si II appear to show asymmetric absorption profiles with blue wings in 4C 41.17. This is a property rarely seen in the spectra of starburst regions or individual hot stars (with the possible exception of some B supergiants). Since these absorption lines are likely to have significant interstellar components, it is certainly possible that these low-ionization lines arise in a galaxian-scale outflow. However, it is unlikely that the blue wing of the Si IV absorption line is also formed in a dense, hot wind from the galaxy driven by supernovae or the AGN. Supernovae-driven ‘super winds’ observed in some starburst galaxies generally exhibit LINER-like line ratios and rarely show strong high-ionization lines (e.g., Lehnert & Heckman 1996) and are therefore unlikely to be the origin of the features observed in 4C 41.17. Absorption observed in broad absorption line (BAL) QSOs exhibit high-ionization lines, but these tend to show absorption extending over a very large velocity range ( $>3000 \text{ km s}^{-1}$ ) and are not spatially extended sources. Nuclear BAL-like absorption seen reflected off dust and gas in the ambient medium can be ruled out by the lack of detectable polarization in 4C 41.17.

Nevertheless, it is worth investigating whether a massive galaxian outflow could result in the observed Si IV profile. A consideration of the energetics of such an outflow and the mass of outflowing material necessary to produce the observed high-ionization line profiles may provide a method by which to discriminate between the ‘galaxian outflow’ and ‘stellar wind’ hypotheses described above. Although a detailed estimate of these quantities is beyond the scope of this paper, a very rough calculation can be used to show that the amount of mass implied by the absorption in the blue wing of Si IV $\lambda$ 1393 is large if this blue wing arises in an outflowing galaxian wind. The blue wing of the Si IV line has a rest frame equivalent width of  $\approx 1.5\text{\AA}$ . Although this line may be saturated, the *minimum* column density required to produce the line is  $N_{\min}(\text{SiIV}) \approx 1.1 \times 10^{14} (W_{\text{SiIV}}/1\text{\AA}) \text{ cm}^{-2}$ . The mass of the Si IV absorbing region (i.e., the region of the outflow with velocities between  $700 \text{ km s}^{-1}$  and  $2500 \text{ km s}^{-1}$  blueward of the systemic velocity) is

$$M_{\min}(\text{SiIV region}) > 8 \times 10^8 \left( \frac{X_{\text{Si}}}{X_{\text{Si,cosmic}}} \right)^{-1} d_{\text{Si}}^{-1} h_{50}^{-2} \text{ M}_{\odot},$$

where  $X_{\text{Si}}/X_{\text{Si,cosmic}}$  is the abundance of Si in 4C 41.17 relative to the cosmic abundance, and  $d_{\text{Si}}$  is the depletion of Si onto dust grains. We have assumed that the continuum emitting region is  $21.6 \times 10.8 \text{ kpc}$  in size, and used the measured Si IV rest equivalent width of  $1.5\text{\AA}$ . For the purposes of this order of magnitude estimate, we have assumed that the ion fraction of Si IV is the maximum possible in thermal equilibrium (i.e., at  $T \sim 10^5 \text{ K}$ ; Shull & Van Steenberg 1982). The energy input required to drive this minimum mass is equivalent to that of  $> 8 \times 10^6$  supernovae. Recent determinations of the abundances in  $z \sim 4$  damped Ly $\alpha$  absorbers have resulted in estimates of  $[\text{Si}/\text{H}] \approx -2$  (i.e.,  $X_{\text{Si}}/X_{\text{Si,cosmic}} \approx 10^{-2}$ ) in undepleted gas (Lu et al. 1996), suggesting that the minimum mass estimate derived above may be higher by at least two orders of magnitude. Also,  $M_{\min}$  corresponds solely to the mass in the region in velocity space in which the blue wing of the Si IV feature is formed; accounting for the probable line saturation, the range of ionization states

and velocities that would be present in a real outflow, depletion of Si onto dust grains, and the integration over all solid angles will increase this number further by at least an order of magnitude. This estimate for the mass of the outflowing material in front of the continuum emitting region of the galaxy is therefore potentially very large ( $\sim 10^{11} M_{\odot}$ ) and is comparable to the *total* mass of material in the entire system (e.g., van Ojik et al. 1997, Chambers et al. 1990). Although more detailed modelling of the ionization state, velocity structure and geometry of the outflow are required to investigate these constraints further, the order-of-magnitude estimate presented here suggests that it is unlikely that the blue wing of Si IV arises in outflowing material. On the other hand, photospheric emission from hot stars provides not only the one viable explanation for the UV continuum emission observed from 4C 41.17 (§ 4.1), but also a natural origin for the blue wings of the high ionization absorption line profiles.

One of the main differences between the spectrum of 4C 41.17 and those of nearby star-forming galaxies is that the spectrum of 4C 41.17 is dominated by strong line emission, which is likely the result of photoionization by the hard spectrum of the active nucleus and possibly shock ionization resulting from the interaction of the radio source plasma with the ambient medium. As discussed in §3.2 the C III]/C IV/He II ratios suggest a high ionization parameter with high energy photons, implying that the observed emission lines are not due to photoionization by starlight, but instead to photoionization by the hard AGN spectrum (e.g., Villar-Martin et al. 1996) or fast shocks (e.g., Dopita & Sutherland 1996). The AGN-driven emission lines dilute the stellar and interstellar absorption lines weakening their observed strengths, and overwhelm the much weaker emission component that may be associated with stellar wind features (i.e., the ‘true’ P-Cygni profiles). Although the emission lines are not powered by hot stars, it is intriguing that a fairly good fit to the overall spectrum of 4C 41.17 can be produced by adding strong emission lines to the spectrum of NGC 1741B1, suggesting that the UV *continuum* emission shortward of C IV may indeed be starlight.

In summary, although the present data are inadequate to unambiguously discriminate between stellar wind and galaxian outflow origins for the resonance absorption transitions, several lines of argument suggest that the UV continuum emission at wavelengths  $\lesssim 1600\text{\AA}$  is dominated by light from a young, hot stellar population. The detection of S V, the marginal detection of Si III, the blue wing of the Si IV profile, the unpolarized continuum emission, the inability of AGN-related processes to account for the UV continuum flux and the overall similarity of the spectra of 4C 41.17 and NGC 1741B1 together provide a compelling argument for the existence of starlight in this  $z = 3.8$  galaxy. If the stellar populations in 4C 41.17 and NGC 1741B1 have similar metallicities and initial mass function (IMF), the similarity of the shape and equivalent width of the blue wing of Si IV in 4C 41.17 and NGC 1741B1 may reflect comparable numbers of hot stars per unit mass in the two systems. The high-ionization resonance lines may therefore have both stellar and interstellar components: our observations are consistent with the hypothesis that the high-velocity blue-wings of the Si IV and C IV absorption are produced in fast winds from hot stars, whereas the absorption associated with the lower ionization states arises in the larger scale dense, galaxian wind. A test of this hypothesis can be provided by detections of the fainter stellar photospheric lines, but this must await higher signal-to-noise and higher resolution spectroscopy. The discussion in the remainder of this paper is based on our favoured interpretation that the UV continuum spectrum of 4C 41.17 is

dominated by the emission from a young stellar population.

### 4.3. The Age of the Stellar Population

If the observed UV continuum emission is indeed due entirely to starlight, the slope of the continuum and the profiles of the stellar absorption lines can be used to constrain the global properties of the stellar population. Since our spectral extraction samples a large volume of the galaxy (our  $2''.1 \times 1''.0$  aperture corresponds to  $21.6 \times 10.8 h_{50}^{-1}$  kpc for  $q_0=0.1$ ), it is very plausible that we are observing a mix of stellar populations corresponding to a range of ages rather than a burst of a single age. Nevertheless, the absorption lines in the integrated spectrum can provide a few constraints on the luminosity-weighted mean age of the stellar population dominating the UV light. Detailed spectral synthesis of the UV spectrum of 4C 41.17 will be presented by Vacca & Dey (1997); in this section, we present some preliminary conclusions based on the general appearance of the spectrum.

We may constrain the upper mass cutoff ( $M_{\text{up}}$ ) of the IMF and the age of the stellar population by using the Si IV absorption feature. As discussed above, although the strong, narrow low-velocity components of the Si IV doublet are largely interstellar, the high-velocity blue wing of the profile (Figure 5) is probably formed in hot stellar winds. The Si IV line is a powerful age diagnostic, as it only appears in the integrated light of young populations (ages  $< 1$  Gyr), reaching maximum strength in B0/B1 stars (Leitherer et al. 1996), with broad, blue-shifted wings of the profile being formed in supergiant winds. Since this absorption line is observed only in massive stars, the very presence of a broad Si IV line implies an  $M_{\text{up}} > 40 M_{\odot}$ . In addition to the Si IV line, the S V  $\lambda 1502$  absorption line is weakly detected in the integrated spectrum. This line is only observed in the spectrum of O-type stars, is weaker in late O and early B subtypes, and no longer detectable in the spectra of mid B subtypes (Walborn et al. 1985, 1995b). Hence, the UV light is dominated by a very young population, implying that the stars were formed in a burst less than a few million years before, or (more likely) that we are observing 4C 41.17 during an epoch of ongoing star formation.

An additional constraint is provided by the shape of the UV spectrum. The population synthesis models of Leitherer and Heckman (1995) demonstrate that the UV spectrum of a young star-forming population can never be bluer than  $F_{\lambda} \propto \lambda^{-2.6}$ , and should gradually redden with age. Hence, the observed slope of the spectrum of 4C 41.17 ( $\lambda^{-1.8}$ ) provides an upper limit on the age and the extinction. In the absence of any extinction, the constant star-formation solar metallicity Salpeter IMF models of Leitherer & Heckman (1995) imply maximum ages for the stellar population of  $\lesssim 600$  Myr. If there is a moderate amount of extinction then the intrinsic slope of the UV spectrum of 4C 41.17 will be bluer than the observed slope and the age will be younger. The extinction for 4C 41.17 is probably not larger than  $E(B - V) \sim 0.1$  mag, because the intrinsic slope would then be bluer than the bluest model values. (Here we have assumed the extinction law given by Kinney et al. 1994. The change in the slope as a function of reddening for this extinction law is given by Leitherer et al. 1996.)

For the instantaneous burst model, the UV continuum slope should become redder much faster than in a continuous star formation scenario. Using the same arguments about the continuum slope

as those given above, we can place an upper limit of about 16 Myr for the age of the population. For an instantaneous burst model, the line profiles place much stronger constraints on the age and  $M_{up}$  than in the continuous (constant-rate) star formation case, since high-velocity blue wings are only observed for ages less than 6 Myr and  $M_{up} > 30 M_{\odot}$ . If the age is less than 6 Myr, then the intrinsic spectral shape of the continuum emission must be between  $F_{\lambda} \propto \lambda^{-2.1}$  and  $F_{\lambda} \propto \lambda^{-2.6}$ , which implies that the observed continuum is moderately reddened ( $E(B-V)=0.04$  to  $0.10$ ). Again, this age estimate is based on the assumption that the Si IV emission component is from hot stars rather than from the AGN.

An additional constraint on the stellar content of 4C 41.17 may be derived from existing near-infrared photometry. The near-infrared  $J$  and  $K_S$  bands are largely uncontaminated by strong line emission from 4C 41.17. In the  $1''.0 \times 2''.1$  spectroscopic aperture discussed here, 4C 41.17 has measured magnitudes of  $J = 21.8 \pm 0.4$  and  $K_S = 20.7 \pm 0.5$  (Adam Stanford, personal communication). Under the null hypothesis that all the observed near-infrared and optical emission is starlight, we find that unreddened, young continuous (constant-rate) star-forming models with ages less than  $\sim 300$  Myr and instantaneous burst models with ages less than  $\sim 16$  Myr that match the observed optical spectrum do not fit the observed near-infrared fluxes. In fact, these simple unreddened models do not provide satisfactory fits to both the  $J$  and  $K_S$  fluxes at any age, either overpredicting the  $K_S$  flux or underpredicting the observed  $J$  flux. In contrast, slightly reddened ( $E(B - V) = 0.1$ ), models with ages 4–20 Myr (for instantaneous burst models) or 10–300 Myr (for continuous star-forming models) provide a satisfactory fit to both the overall optical-IR spectral energy distribution and (at the young age end) to the Si IV line profile. If the observed infrared emission contains a reddened AGN component, the spectral energy distribution of the underlying population is bluer than observed, and therefore younger. If the population is indeed young ( $\lesssim 1$  Gyr), then a reddened AGN can contribute no more than 60–65% of the total  $K_S$  flux.

In summary, if the galaxy is forming stars continuously, the age (derived from its UV spectrum) is less than 600 Myr. The age estimates presented in this section are at present phenomenological and are uncertain as they depend upon several assumptions regarding the shape of the IMF, the star-formation history, the metallicity of the star-forming population, and the reddening intrinsic and along the line-of-sight to 4C 41.17. Nevertheless, it is of considerable interest that a simple model can provide an adequate fit to both the observed optical and near-infrared continuum fluxes of 4C 41.17, suggesting that stronger constraints may be eventually derived when high signal-to-noise moderate resolution optical and infrared spectra of the UV light and the 4000Å or Balmer-break region are available.

#### 4.4. The Structure of the Galaxy and the Case for Triggered Star-formation

In a companion paper, van Breugel et al. (1997) present deep *HST* imaging of 4C 41.17, and demonstrate that the brightest central region is composed of several compact ( $\lesssim 5$  kpc) knots, which are distributed in an ‘edge-brightened’ structure suggestively lying on the outer envelope of the central radio source structure (also see Figure 1). The deep spectroscopic data presented in

this paper strongly suggest that the UV absorption–line spectra of these knots are similar to that of star–forming regions in nearby galaxies.

If the compact UV knots in 4C 41.17 are indeed star–forming regions, then the spatial distribution of these knots relative to the radio source emission is suggestive of models where star–formation may be triggered by the radio source (De Young 1989, Begelman & Cioffi 1989). De Young (1989) proposed that as radio jets propagate into dense protogalactic gas, star–formation occurs in the compressed post–shock gas as it cools. This results in a spatial distribution of hot stars that is both aligned with the radio source and edge–brightened in the direction normal to the radio jet axis, on a scale of roughly 1 – 4 kpc from the jet axis depending upon the jet parameters and age of the stellar population (De Young 1989). In the scenario proposed by Begelman & Cioffi (1989), star–formation also occurs when intergalactic clouds are overtaken and compressed by the expanding over–pressured cocoon surrounding the radio source. This mechanism can result in a large star–formation rate ( $\sim 100 M_{\odot}/\text{yr}$ ; Begelman & Cioffi 1989) and also results in young stars in an edge–brightened structure (De Young 1989). The observed distribution of star–forming clumps in 4C 41.17 is edge–brightened as predicted in these scenarios, and the spatial extent in the transverse direction is indeed comparable to that expected. The strongly asymmetric radio source morphology (shorter eastern arm) and brightness distribution (the eastern knots are more luminous both in the radio and the optical) also support a picture of stronger ongoing interactions between the radio source and the ambient medium on the eastern side of the galaxy.

Although the evidence presented here (spectroscopy coupled with the van Breugel et al. 1997 *HST* imaging data) is circumstantial, at present there is no clearer support for this picture than these data. Our observations of 4C 41.17 are consistent with the interpretation that the alignment effect in at least this  $z = 3.80$  radio galaxy is due to star formation induced by the radio source, and not due to scattering as is the case in the bulk of the  $z \sim 1$  radio galaxies.

If the continuum emission is indeed due to starlight from a young population, we can use the observed UV continuum luminosity to estimate the star–formation rate in the system. The specific luminosity at  $\lambda_{rest} \approx 1500\text{\AA}$  is  $L_{1500} \approx 2.0 \times 10^{42} h_{50}^{-2} \text{ erg s}^{-1} \text{\AA}^{-1}$  ( $q_0=0.1$ ). For a Salpeter IMF with an upper mass cutoff of  $80 M_{\odot}$ , the stellar population synthesis models of Leitherer et al. (1993) suggest that a continuously star–forming population has  $\log L_{1500} = 39.25 - 40.16$  for ages between 1 and 9 Myr after the onset of star–formation. Hence, if *all* of the  $1500\text{\AA}$  flux in 4C 41.17 is due to young stars, the star–formation rate is between  $140 - 1100 h_{50}^{-2} M_{\odot}/\text{yr}$ . If we account for screen extinction of  $E(B - V)=0.1$ , these estimates are increased by a factor of  $\approx 2.9$ . Although this range is large, at the lower end, this rate is observed for extreme starburst galaxies. For a high–redshift galaxy, possibly in its early stages of formation, such a large rate may be expected. At this sustained rate of star–formation, it will only take  $< 0.7 \text{ Gyr}$  to form a  $10^{11} M_{\odot}$  system of stars, a timescale comparable to the dynamical timescale. This rate of star–formation is higher than that observed in the  $z \sim 2 - 3$  “Lyman–limit” galaxies discovered by Steidel et al. (1996), which are typically observed to have star–formation rates at  $z \sim 3$  of  $10 - 70 h_{50}^{-2} M_{\odot}/\text{yr}$  ( $q_0=0.1$ ). The lower rates observed in these systems may be due to the fact that these galaxies are being observed at a later stage in their history ( $\Delta t \approx 0.75 h_{50}^{-1} \text{ Gyr}$  between  $z = 4$  and  $z = 3$  for  $\Omega = 0.2$ ), or that these are lower–mass systems than 4C 41.17, or that their star–formation rates have been under–estimated due to dust–extinction.

The timescale derived above for the age of the starburst can be compared with the expansion timescale of the radio source. In the instantaneous burst model, the age of the stellar population is less than 16 Myr. During this time, the radio source will expand by roughly  $16.4 (v_{\text{exp}}/1000 \text{ km s}^{-1})(\tau/16 \text{ Myr}) \text{ kpc}$ , or  $\sim 1''.5 h_{50}(v_{\text{exp}}/1000 \text{ km s}^{-1})(\tau/16 \text{ Myr}) \sin \theta$  from the location at which it triggered the star formation, where  $v_{\text{exp}}$  is the radio source expansion speed,  $\tau$  is the age of the population, and  $\theta$  is the angle between the direction of expansion and the line of sight. The lack of a bright core component to the radio source and the absence of any significant AGN component to the UV emission suggest that the radio source is oriented close to the plane of the sky, with our direct view of the nuclear region obscured by dust. Hence, since the UV continuum emission is observed to be roughly coincident with the radio emission in the central regions (Miley et al. 1992, Carilli et al. 1994), we may conclude that the triggering was recent, or that the radio source is expanding slowly, or both.

The large star-formation rate derived for 4C 41.17 requires a large reservoir of cold gas. Indeed, there is some evidence for an extended cold component from the observation of spatially extended Ly $\alpha$  absorption in 4C 41.17 (Hippelein & Meisenheimer 1993, van Ojik et al. 1997, Dey et al. 1997b) suggesting at least  $\sim 4 \times 10^7 h_{50}^{-2} \text{ M}_{\odot}$  of cold gas in the central regions, and  $\sim 10^9 h_{50}^{-2} \text{ M}_{\odot}$  in a large extended halo ( $q_0=0.1$ ). In addition, the detection of submillimeter emission from 4C 41.17 implies that the galaxy contains a very large mass in dust ( $M_{\text{dust}} \sim 8 \times 10^8 h_{50}^{-2} \text{ M}_{\odot}$  for  $q_0=0.1$ ; Dunlop et al. 1994), and suggests the presence of such a reservoir. Under the assumption that the dust is heated purely by starlight, Dunlop et al. derive star-formation rates of  $\sim 5 \times 10^3 h_{50}^{-2} \text{ M}_{\odot}/\text{yr}$  ( $q_0=0.1$ ); although there may be a significant AGN contribution to the dust heating, it is noteworthy that this estimate is of the same order of magnitude as the estimates derived above from the UV luminosity alone. The blue UV/optical color and lack of strong color gradients in 4C 41.17 implies that the observed continuum emission is not very reddened, and is likely to be indicative of an asymmetric distribution of dust. We speculate that 4C 41.17 may well be a young galaxy emerging from its dust cocoon, with only the very outer regions visible at present.

#### 4.5. Is 4C 41.17 a Typical Evolutionary Predecessor of the $z \sim 1$ Powerful Radio Galaxies?

In addition to its different polarization properties, 4C 41.17 also exhibits an important morphological difference at rest-frame UV and optical wavelengths compared to lower redshift objects. The  $z \sim 1$  3CR radio galaxies tend to be clumpy and spatially extended in the rest-frame UV, whereas their rest-frame optical morphologies (observed near-IR) are generally more symmetric; i.e., rather than reflecting the peculiar UV structures, the optical structures look more like ‘normal’ elliptical galaxies. 4C 41.17 also has a clumpy UV morphology (van Breugel et al. 1997), but its rest-frame optical morphology is also clumpy and extended along the major axis of the radio emission (Chambers et al. 1990); in fact, there is near spatial coincidence between the rest-frame UV and optical emission (Graham et al. 1995). Although the rest wavelengths sampled at these different redshifts are different, the  $z \sim 1$  radio galaxies exhibit a noticeable morphological change across the 4000Å break (i.e., the approximate wavelength beyond which stars begin to dominate over the AGN component), whereas 4C 41.17 ( $z = 3.80$ ) does not exhibit this property.



The dissimilarity between the polarization and morphological properties of 4C 41.17 and those of the lower redshift powerful radio galaxies raises the intriguing question of whether we are witnessing an evolutionary phenomenon. A tempting hypothesis is that radio galaxies at  $z \gtrsim 4$  are in the process of formation: they are forming stars on the dense borders of the expanding cocoon inflated by the radio lobes (e.g., Begelman & Cioffi 1989), and their UV and optical emission is dominated by the light from young stellar populations. The AGN component, scattered or directly viewed, is likely to be diluted by the young starlight. In contrast, in the  $z \sim 1$  radio galaxies, the population has aged and dynamically relaxed, and no longer contributes any significant flux to the UV spectrum. The UV light in the  $z \sim 1$  population may instead be dominated by other blue components, such as the AGN light (viewed directly or scattered by dust and electrons in the ambient medium) remnant star-forming regions, or Balmer continuum emission from the photo- and shock-ionized gas. In an  $H_0=50$ ,  $\Omega=0.2$  Universe, the time between  $z = 3.8$  and  $z = 1$  is  $\approx 4.8$  Gyr, providing ample time for the population to age and (possibly) dynamically relax to explain the colors and morphology of the stellar component in  $z \sim 1$  radio galaxies. Recent spectral synthesis modelling of the UV spectra of  $z \sim 1.5$  lower-power radio galaxies which have no discernible light contribution from the AGN result in age estimates of  $\gtrsim 3.5$  Gyr, consistent with this picture (Dunlop et al. 1996, Spinrad et al. 1997, Dey et al. 1997a).

## 5. Conclusions

We have presented deep spectropolarimetric observations of one of the most distant known radio galaxies, 4C 41.17 at  $z = 3.80$ . The spectrum is dominated by strong emission lines (possibly excited by shocks and / or photoionization by the AGN), a bright UV continuum emission and fairly strong resonance absorption lines of both low- and high-ionization species. The UV continuum emission from the brightest regions in this galaxy is unpolarized ( $P_{2\sigma} < 2.4\%$ ), suggesting that scattered AGN light may not be a dominant contributor to the UV flux from the galaxy. Many of the lines exhibit P-Cygni-like profiles, i.e., emission components associated with blue-shifted absorption components. The UV absorption spectrum is similar to that of star-forming regions in nearby starburst galaxies, and to the spectra of the recently-discovered high-redshift population of starburst systems. Most of the strong low-velocity narrow absorption lines most likely arise in the interstellar medium of 4C 41.17. However, we report a detection of the S V $\lambda$ 1502 absorption line which arises in the photospheres of O-type stars and is uncontaminated by interstellar absorption, and also a possible detection of the Si III stellar photospheric lines. We also find that the shape of the high-velocity blue wing of the Si IV doublet is similar to that observed in nearby starburst galaxies such as NGC 1741, where it is interpreted as arising in an O star wind. It appears unlikely that the blue wing of the Si IV line arises in a galaxian outflow since the implied mass in such an outflow is very large. These considerations, combined with the lack of detectable polarization, the lack of strong AGN-like broad-line emission, the inability of other AGN-related processes to produce the bulk of the continuum emission, and the similarity of 4C 41.17's spectrum to that of the star-forming region NGC 1741B1, together provide a compelling argument that the UV spectrum of 4C 41.17 is dominated by starlight from a young stellar population.

If the UV continuum emission is entirely dominated by starlight, instantaneous burst solar

metallicity population synthesis models imply an age of less than 16 Myr, and suggest that the spectrum is reddened by dust either intrinsic to 4C 41.17 or along the line of sight. If the star-formation is continuous, then the age of the population is  $\lesssim 600$  Myr. Under the assumption that *all* of the  $1500\text{\AA}$  flux in 4C 41.17 is due to young stars, the star-formation rate is between  $140 - 1100 h_{50}^{-2} M_{\odot}/\text{yr}$ . A fairly young, slightly reddened population provides an adequate fit to the overall spectral energy distribution, but there potentially could be a red AGN which dominates the near-infrared emission.

4C 41.17 is one of the highest redshift aligned radio galaxies known. Our data suggest that the UV properties of this galaxy are different from those of  $z \sim 1$ , aligned radio galaxies: the unpolarized UV continuum emission and the edge-brightened, clumpy *HST* morphology combined with the spectroscopic evidence of a starburst-like spectrum may imply that the UV light is dominated by young stars forming on the dense edge of the pressurized cocoon formed by the radio source, as suggested by Begelman & Cioffi (1989). If so, we are witnessing this galaxy in the process of formation. The young age derived for the starburst in 4C 41.17 is consistent with the observation that the radio continuum emission is roughly spatially coincident with the UV emitting regions. The ages determined for the  $z \sim 1$  radio galaxies are consistent with the hypothesis that these objects form the bulk of their stars at  $z \sim 4$  in a low-density Universe.

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Table 1. Measured Continuum and Emission Line Polarizations<sup>†</sup>

$\Delta\lambda_{obs}(\text{\AA})$	$\Delta\lambda_{rest}(\text{\AA})$	$Q(\%)$	$U(\%)$	$P(\%)$	$P_{unb}(\%)$	$\theta(^{\circ})$	Note
5500–5800	1146–1208	$3.43\pm3.40$	$-0.55\pm3.12$	3.48	$0.76\pm3.39$	$-4.56\pm27.96$	
5800–5870	1208–1223	$-0.71\pm0.26$	$-0.91\pm0.26$	1.15	$1.12\pm0.26$	$115.98\pm6.43$	Ly $\alpha$
5825–5845	1213–1218	$-0.29\pm0.22$	$-0.14\pm0.23$	0.32	$0.23\pm0.22$	$102.95\pm19.91$	Ly $\alpha$ (narrow)
5870–7370	1223–1535	$0.92\pm0.58$	$1.02\pm0.56$	1.37	$1.25\pm0.57$	$24.04\pm11.80$	
7370–7480	1535–1558	$4.57\pm1.15$	$0.57\pm1.14$	4.61	$4.46\pm1.15$	$3.55\pm7.16$	C IV
7480–7810	1558–1627	$-2.01\pm1.80$	$1.06\pm1.70$	2.27	$1.41\pm1.78$	$76.13\pm22.43$	
7845–7900	1634–1646	$-4.26\pm2.93$	$-3.99\pm2.87$	5.84	$5.07\pm2.90$	$111.59\pm14.24$	He II
7895–9050	1645–1885	$-3.65\pm1.57$	$2.01\pm1.37$	4.17	$3.88\pm1.53$	$75.59\pm10.49$	
9100–9200	1896–1917	$3.99\pm2.58$	$-4.56\pm2.45$	6.06	$5.52\pm2.51$	$-24.43\pm11.85$	C III]

<sup>†</sup>Measured in an aperture of size  $3''.4\times1''.0$ .

Table 2. Emission Line Measurements

Line	$\lambda_{rest}(\text{\AA})$	$\lambda_{obs}(\text{\AA})$	$F_{obs}^{\dagger}$	FWHM (km s <sup>-1</sup> )	$W_{\lambda}^{obs}(\text{\AA})$
Ly $\alpha$ (narrow)	1215.67	$5835.5\pm0.1$	$771\pm37$	$613\pm13$	548
Ly $\alpha$ (broad)	1215.67	$5835.5\pm0.1$	$689\pm41$	$1373\pm45$	490
N V	1238.81	$5946.8\pm0.5$	$16.9\pm1.8$	$628\pm48$	10.6
N V	1242.80	$5965.9\pm0.5$	$21.8\pm1.9$	$628\pm48$	13.7
Si II	1264.89	$6071.6\pm1.1$	$6.4\pm1.4$	$546\pm106$	4.0
Si IV	1393.76	$6691.0\pm1.8$	$8.6\pm2.3$	$1134\pm172$	6.3
Si IV	1402.77	$6734.2\pm1.8$	$11.5\pm1.5$	$1134\pm172$	8.4
C IV	1548.20	$7428.9\pm0.2$	$74.7\pm1.8$	$541\pm14$	58.8
C IV	1550.77	$7441.2\pm0.2$	$57.0\pm1.6$	$541\pm14$	44.8
He II	1640.46	$7870.7\pm0.4$	$55.3\pm2.8$	$553\pm28$	51.2
C III](narrow)	1908.73	$9152.5\pm0.6$	$19\pm15$	$511\pm151$	17.0
C III](broad)	1908.73	$9152.5\pm0.6$	$72\pm15$	$1120\pm135$	64.6

<sup>†</sup>All fluxes are measured in an aperture of  $2''.1\times1''.0$ , and are in units of  $10^{-18}$  erg s<sup>-1</sup> cm<sup>-2</sup>. The line fluxes have been corrected for Galactic reddening using  $E(B - V) = 0.15$  and the extinction curve of Cardelli, Clayton & Mathis (1989).

Table 3. Absorption Line Measurements

$\lambda_{obs}$ (Å)	$W_{\lambda}^{obs}$ (Å)	FWHM (km s <sup>-1</sup> )	Identification	Comments
5799.2±0.8	43.1±2.0	2022±92	Ly $\alpha$	P-Cygni-like
	<1.5		C III $\lambda$ 1247	Stellar
6047.8±0.9	5.3±0.9	558±117	Si II $\lambda$ 1260.4	
6226.3±2.0	3.7±1.2	664±278	Si III $\lambda\lambda$ 1294.6,1296.7?	Stellar?
6246.4±1.0	6.8±1.3	639±162	O I $\lambda$ 1302.2+Si II $\lambda$ 1304.4	
6351.5±1.1	1.4±1.4	735±968	C II $\lambda$ 1334.5?	
6396.1±2.4	5.5±1.2	947±219	C II $\lambda$ 1334.5	
6544.3±0.4	3.1±0.7	218±63	Mg II $\lambda$ 2796.4 at z=1.34?	Foreground?
6560.0±1.1	6.6±1.2	654±152	Mg II $\lambda$ 2803.5 at z=1.34?	Foreground?
6573.6±1.0	1.6±0.6	263±78	O V $\lambda$ 1371?	Stellar?
6661.8±3.0	4.2±1.5	931±456	Si IV?	
6680.5±0.7	5.5±1.2	445±69	Si IV $\lambda$ 1393.8	P-Cygni-like
6708.0±1.3	2.3±0.8	362±92	Si IV $\lambda$ 1402.8	P-Cygni-like
	<1		Si III $\lambda$ 1417	Stellar
7207.7±0.8	2.0±0.5	416±84	S V $\lambda$ 1502	Stellar
7256.5±3.8	3.5±1.3	754±285	Si II $\lambda$ 1526.7?	
7326.5±2.3	7.2±2.2	739±310	Si II $\lambda$ 1526.7	
7386.0±5.3	5.0±3.0	748±210	C IV $\lambda$ 1548.2	P-Cygni-like
7398.3±5.3	3.7±3.0	748±210	C IV $\lambda$ 1550.8	P-Cygni-like
	<3		N IV $\lambda$ 1720	Stellar

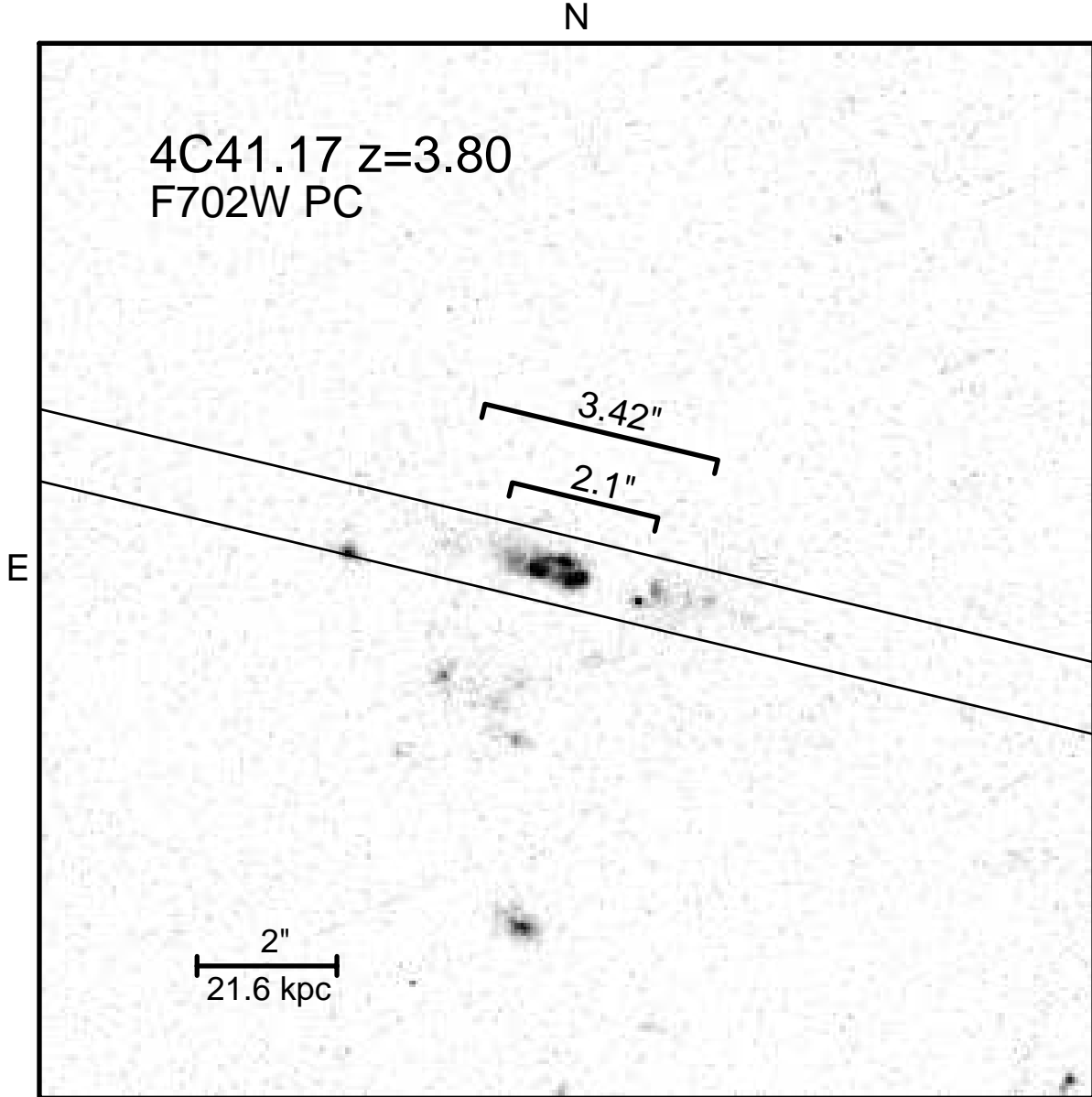


Fig. 1.— Broad band F702W image of 4C 41.17 from van Breugel et al. 1997. The field of view is  $\approx 15'' \times 15''$ . The galaxy is at  $\alpha = 06^h 50^m 52^s.16$ ,  $\delta = 41^\circ 30' 30''.8$  (J2000). The parallel lines denote the position and orientation of the  $1''$  slit used in our Keck LRIS spectropolarimetric observations oriented in  $PA=76.5^\circ$ . The scale shown is for a cosmology with  $H_0=50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0=0.1$ .



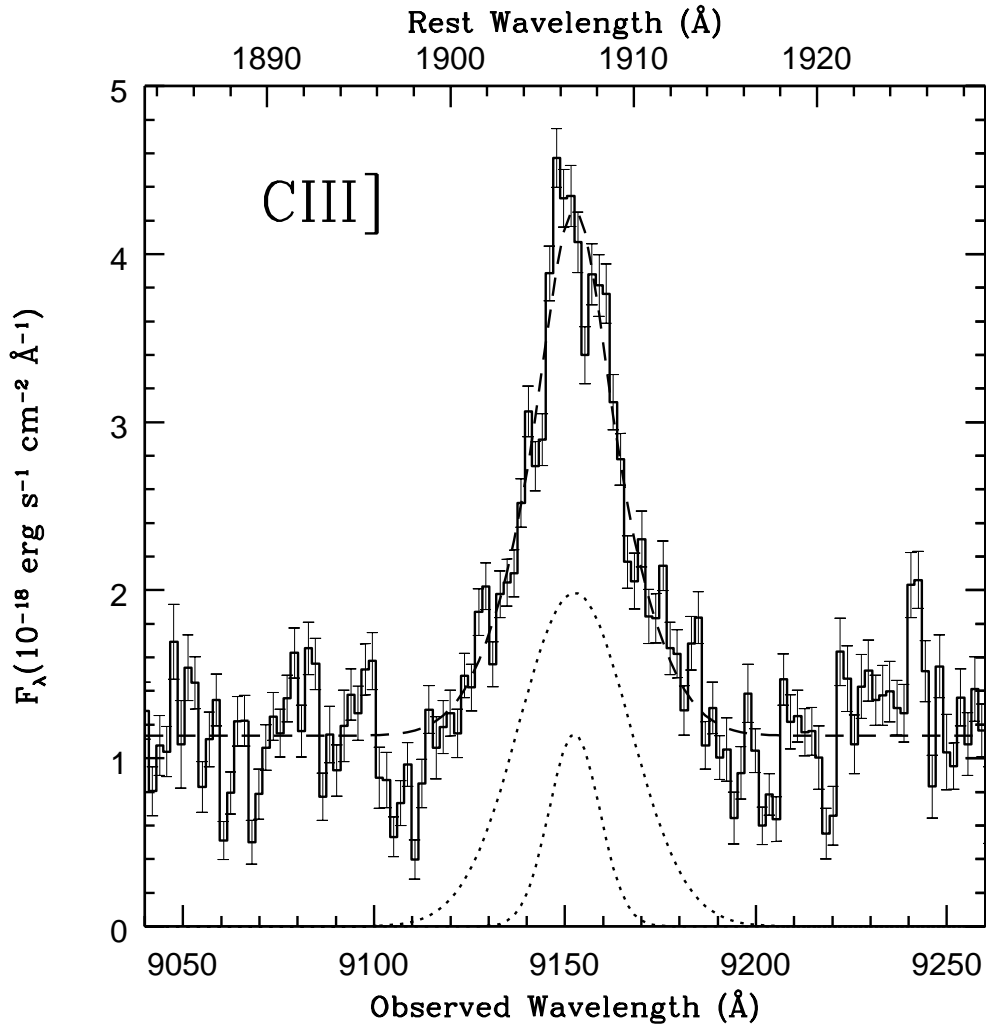


Fig. 2.— Two-component Gaussian fit to the CIII] emission line. The solid line denotes the observed spectrum measured in a  $2'' \times 1''$  aperture (along with  $1\sigma$  error bars), and the dashed line the fit to the profile obtained by forcing the broad and narrow components to have the same central wavelength. The dotted lines at the bottom of the plot show the broad and narrow components of the fit.

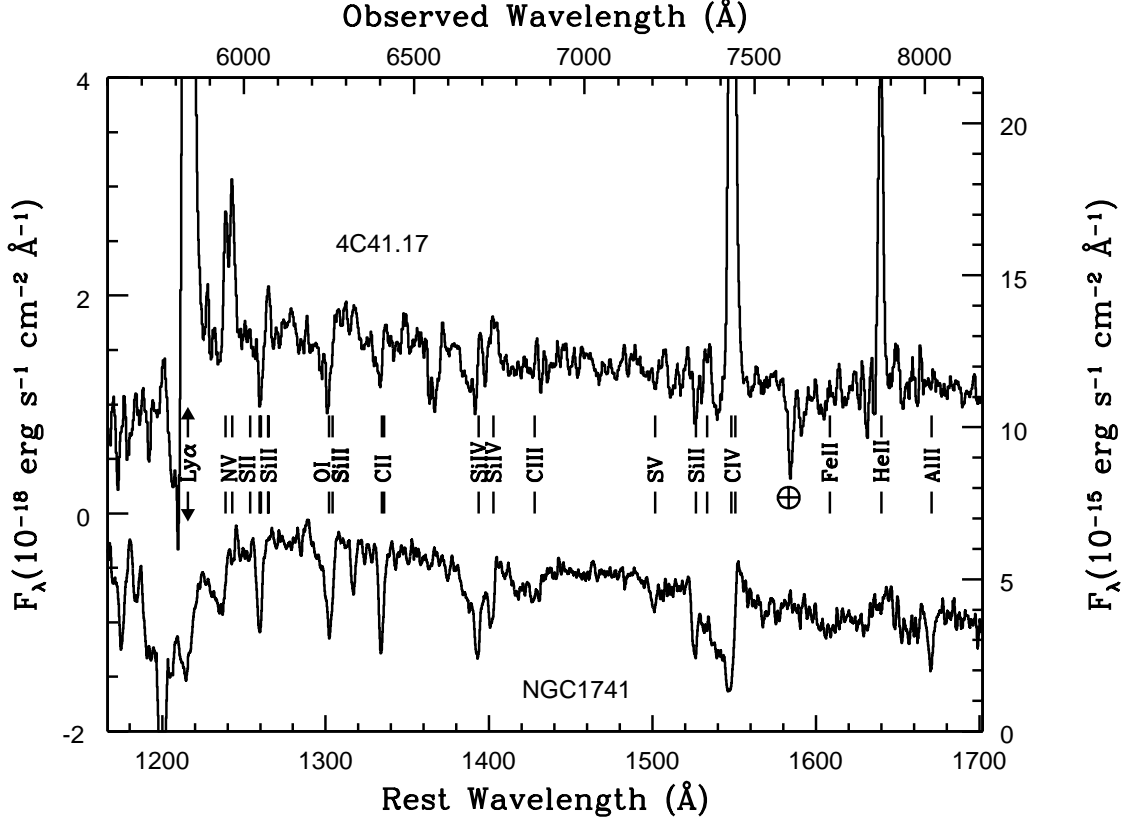


Fig. 3.— Total light spectrum of the central  $2'' \times 1''$  of 4C 41.17 compared with the UV spectrum of the B1 star-forming knot in the nearby Wolf-Rayet starburst galaxy NGC 1741 from Conti et al. (1996). The ordinate is labelled with the flux density scales for 4C 41.17 and NGC 1741B1 on the left and right axes respectively. The two spectra show many similarities in their absorption line properties, although the emission line spectrum of 4C 41.17 is dominated by processes related to the AGN. The absorption spectrum is also similar to that of the recently discovered population of starburst galaxies at  $z \lesssim 3$ .

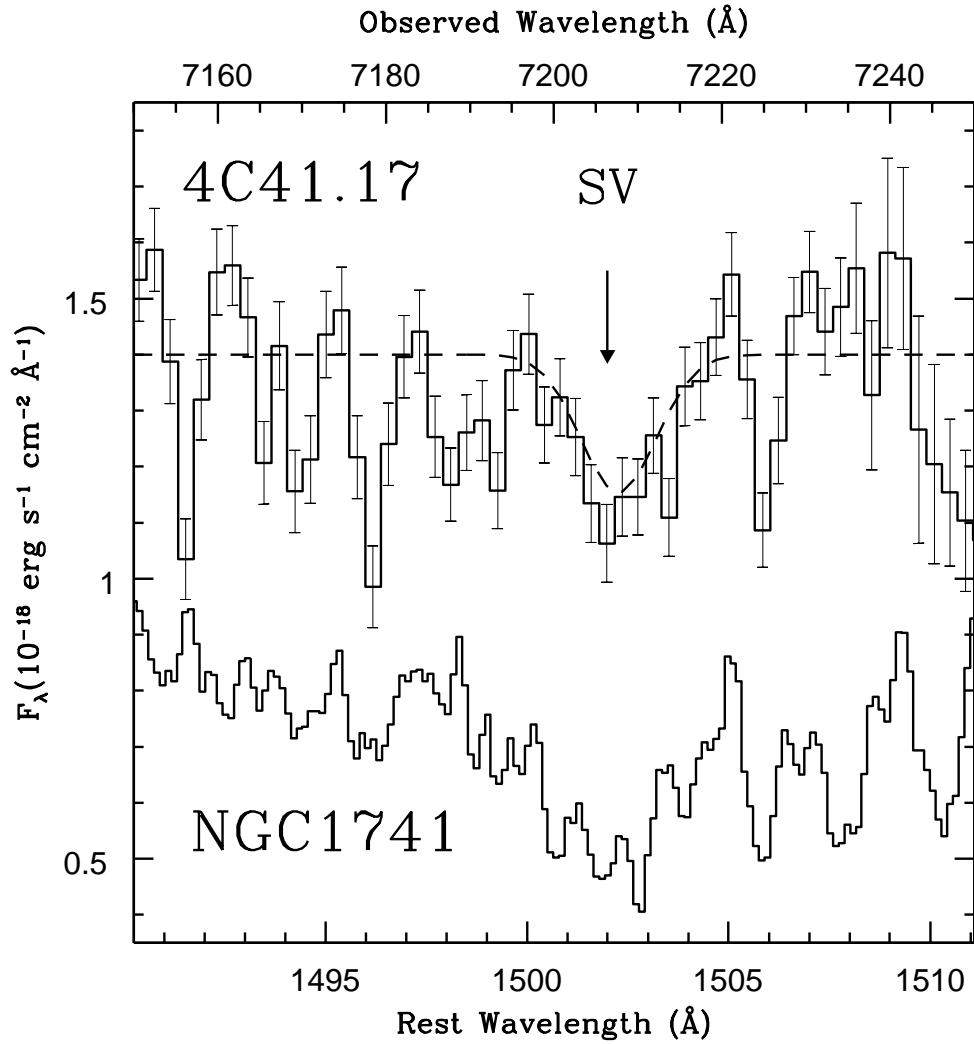


Fig. 4.— The unsmoothed total light spectrum of the central  $2'' \times 1''$  of 4C 41.17 compared with the *HST* spectrum of NGC 1741B1 (Conti et al. 1996) in the spectral region surrounding the SV $\lambda$ 1502 stellar photospheric absorption line. Formal 1- $\sigma$  error bars are plotted for the spectrum of 4C 41.17. The spectrum of NGC 1741B1 has been scaled to match the continuum level of the 4C 41.17 spectrum, and then offset by 0.7 units. A gaussian fit to the SV absorption line feature is shown.

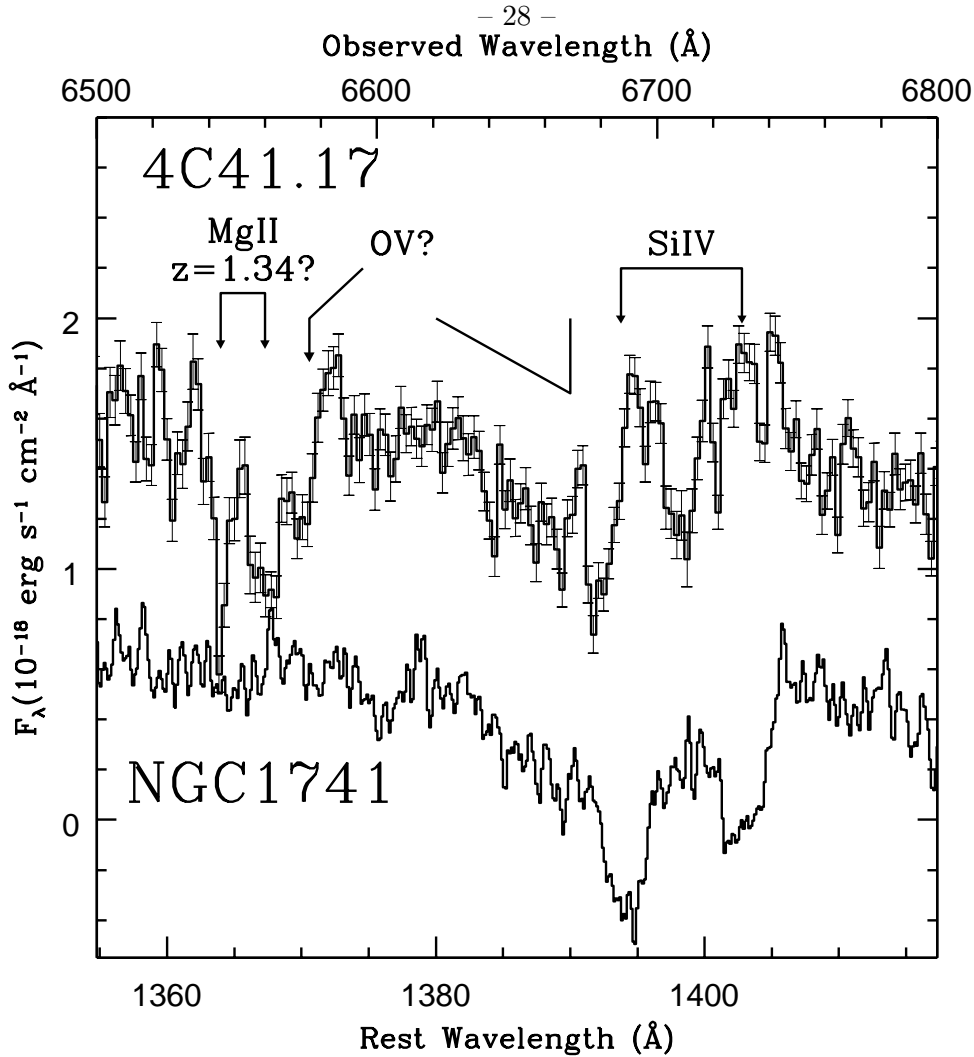


Fig. 5.— The unsmoothed total light spectrum of the central  $2'' \times 1''$  of 4C 41.17 compared with the *HST* spectrum of NGC 1741B1 (Conti et al. 1996) in the spectral region of the SiIV  $\lambda\lambda 1393.8, 1402.8$  absorption lines. Formal  $1\text{-}\sigma$  error bars are plotted for the spectrum of 4C 41.17. The spectrum of NGC 1741B1 has been scaled to the match the continuum level of the 4C 41.17 spectrum, and then offset by 1.1 units. The connected arrows at  $\lambda_{rest} \sim 1400\text{\AA}$  represent the systemic velocity of the SiIV lines as determined from the HeII emission redshift. Note that the narrow absorption components at the systemic velocity are largely filled in by emission. The narrow components immediately blueward of the arrows are likely to be largely interstellar. However, the blue wing (denoted by the wedge and also observed in the spectrum of NGC 1741B1) may be formed in winds from hot stars. The two blue components of the composite absorption feature at  $6555\text{\AA}$  are probably due to a foreground MgII absorption system at  $z \approx 1.34$ . The reddest component may have a contribution from the OV $\lambda 1371$  O star wind feature.